Leptoquarks in *D* meson decays

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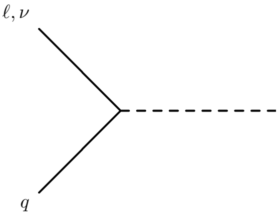


Low-energy leptoquarks

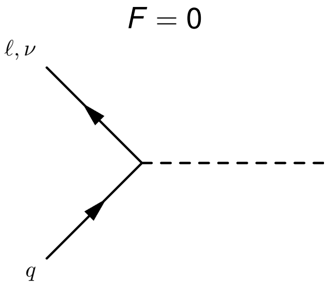
Bosonic particle, carying both *L* and *B*. Assumptions:

- lepton-quark-*LQ* vertices are of dimension 4 and are invariant under the SM gauge group
- no coupling to diquarks, to avoid bounds from proton decay

Table 1: Possible leptoquarks and their quantum numbers.

Spin	$3B+L$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	Allowed coupling
0	-2	$\bar{3}$	1	$1/3$	$\bar{q}^c_L \ell_L$ or $\bar{u}^c_R e_R$
0	-2	$\bar{3}$	1	$4/3$	$\bar{d}^c_R e_R$
0	-2	$\bar{3}$	3	$1/3$	$\bar{q}^c_L \ell_L$
1	-2	$\bar{3}$	2	$5/6$	$\bar{q}^c_L \gamma^\mu e_R$ or $\bar{d}^c_R \gamma^\mu \ell_L$
1	-2	$\bar{3}$	2	$-1/6$	$\bar{u}^c_R \gamma^\mu \ell_L$
0	0	3	2	$7/6$	$\bar{q}_L e_R$ or $\bar{u}_R \ell_L$
0	0	3	2	$1/6$	$\bar{d}_R \ell_L$
1	0	3	1	$2/3$	$\bar{q}_L \gamma^\mu \ell_L$ or $\bar{d}_R \gamma^\mu e_R$
1	0	3	1	$5/3$	$\bar{u}_R \gamma^\mu e_R$
1	0	3	3	$2/3$	$\bar{q}_L \gamma^\mu \ell_L$

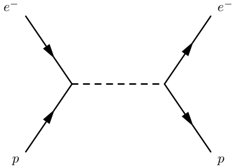
Low-energy leptoquarks



- color triplets, many possible $SU(2)_L$ and $U(1)_Y$ assignments
- arise naturally in unification theories, Pati-Salam, R-parity violating SUSY (squarks), extended technicolor, compositeness models

Direct searches

- Single production at $e^{\pm}p \rightarrow e^{\pm}p$ experiments (HERA, ZEUS)
  $\Rightarrow$ Constraints in the coupling-mass plane



- Pair production in hadron colliders

S. Abdullin, F. Charles / Physics Letters B 464 (1999) 223–231

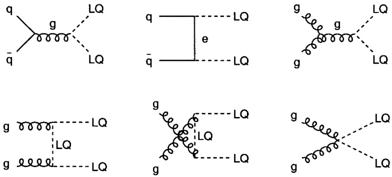
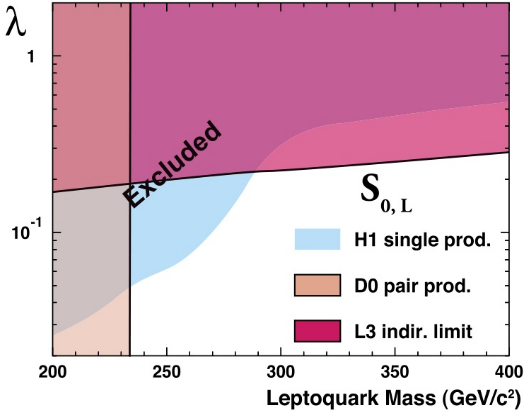


Fig. 1. Leptoquark pair production diagrams.

Yukawa coupling independent - direct constraint on mass

- False indication for on-shell production in HERA *ep* scattering (1997)

Lower bound on mass from D0,CDF $\sim 230 - 250\ \mathrm{GeV}$ for leptoquarks coupled to 1st or 2nd generation



Indirect bounds

- Strong constraint on 1st generation LQs from $\pi^+ \to e\nu_e/\pi^+ \to \mu\nu_\mu$
  - forbids nonchiral leptoquarks in the 1st generation, since they would lift the helicity suppression and destroy

$$\frac{\mathcal{B}(\pi^+ \to e^+\nu_e)}{\mathcal{B}(\pi^+ \to \mu^+\nu_\mu)} = \frac{m_e^2(m_\pi^2 - m_e^2)^2}{m_\mu^2(m_\pi^2 - m_\mu^2)^2} = 1.2 \times 10^{-4}.$$

- *Generation nondiagonal* LQs mediate FCNCs at tree-level. Even if we impose diagonality on the couplings to left-handed quarks, nontrivial CKM matrix spoils it

f_{D_s} puzzle (Kronfeld, Dobrescu, PRL100,241802)

$$\mathcal{B}(D_s \to \ell\nu)_{SM} \sim f_{D_s}^2 |G_F m_\ell V_{cs}|^2$$

$(f_{D_s})_{exp} = 277 \pm 9\ \mathrm{MeV}$ larger than $(f_{D_s})_{latt.} = 241 \pm 3\ \mathrm{MeV}$ for $3.8\,\sigma$

Lattice or exp. problem ?

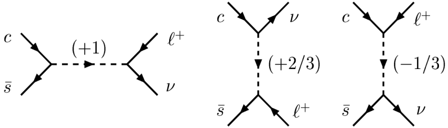
- use of HISQ action for charm quark - good results on m_D, m_{D_s}, f_{D^+}
- same analysis yields f_π and f_K in agreement with exp.
- radiative corrections ($D_s \to \gamma D_s^* \to \gamma\mu\nu$) should be $< 1\%$ for $300\ \mathrm{MeV}$ cut on E_γ (CLEO)

- only two additional 4-fermion operators can affect $D_s \to \mu\nu$:

$$\frac{C_A^\ell}{M^2}(\bar{s}c)_A(\bar{\nu}\ell)_{V-A} \quad \text{and} \quad \frac{C_P^\ell}{M^2}(\bar{s}c)_P(\bar{\nu}\ell)_{S+P}$$

f_{D_s} puzzle

Possible boson exchanges:



The $-1/3$ exchange corresponds to scalar leptoquark in the $(3, 1, -1/3)$ representation

$$\mathcal{L}_{LQ} = \tilde{d}\,\kappa_\ell(\bar{\nu}_\ell P_R s^c - \bar{\ell} P_R c^c) + \tilde{d}\,\kappa'_\ell \bar{\ell} P_L c^c + \mathrm{H.c.},$$

To bring the f_{D_s} discrepancy within $1\,\sigma$:

$$\frac{M}{(\mathrm{Re}\, C_A^\ell)^{1/2}} \lesssim \begin{cases} 710 \text{ GeV for } \ell = \tau \\ 850 \text{ GeV for } \ell = \mu \end{cases},$$

$$\frac{M}{(\mathrm{Re}\, C_P^\ell)^{1/2}} \lesssim \begin{cases} 920 \text{ GeV for } \ell = \tau \\ 4500 \text{ GeV for } \ell = \mu \end{cases},$$

where

$$C_A^\ell = \frac{1}{4}|\kappa_\ell|^2$$

$$C_P^\ell = \frac{1}{4}\kappa_\ell \kappa_\ell'^*$$

f_{D_s} puzzle

"Orthogonal" helicity suppression in $D_s \to \ell\nu$ and $D \to K\ell\nu$

$$\mathcal{L}_{eff}(c \to s\ell\nu) = \mathcal{L}_{SM} + \frac{C^{LL}}{M^2}(\bar{s}c)_{V-A}(\bar{\nu}\ell)_{V-A} + \frac{C^{LR}}{M^2}(\bar{s}c)_{S+P}(\bar{\nu}\ell)_{S+P} + \frac{C^{LR}}{M^2}(\bar{s}\sigma_{\mu\nu}c)(\bar{\nu}\sigma^{\mu\nu}\gamma_5\ell)$$

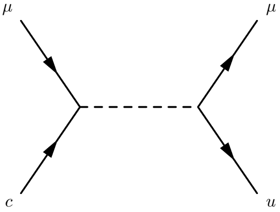
- $(V-A)\otimes(V-A)$ helicity suppr. for $D_s \to \ell\nu$
- $(S+P)\otimes(S+P)$, $T \otimes T\gamma_5$ helicity suppr. for $D \to K\ell\nu$

$\Rightarrow$ Use exp./latt. tension for $K\ell\nu$ mode to constrain C^{LL}, and $\ell\nu$ to find C^{LR} (Benbrik,Chen,0807.2373)

- From additional assumptions on the fermion mixing matrices follows the bound on FCNC process $D \to \mu^+\mu^-$

$D \to \mu^+\mu^-$ and $D^+ \to \pi^+\mu^+\mu^-$

$$\mathcal{L}_{LQ} = \tilde{d}\,\kappa_\ell(\bar{\nu}_\ell P_R s^c - \bar{\ell} P_R c^c) + \tilde{d}\,\kappa'_\ell \bar{\ell} P_L c^c + \text{H.c.},$$



$$\mathcal{L}_{\text{eff}}(c \to u\ell^+\ell^-) = \frac{1}{8M_{\tilde{d}^2}} \left[C^{L*}_{\ell c} C^L_{\ell u}\,(\bar{u}c)_{V-A}(\bar{\ell}\ell)_{V-A} + C^{R*}_{\ell c} C^R_{\ell u}\,(\bar{u}c)_{V+A}(\bar{\ell}\ell)_{V+A} \right.$$
$$+ C^{L*}_{\ell c} C^R_{\ell u} \left(\frac{1}{2}\,(\bar{u}\sigma^{\mu\nu}c)(\bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\ell) - (\bar{u}c)_{S-P}(\bar{\ell}\ell)_{S-P} \right)$$
$$\left. + C^{R*}_{\ell c} C^L_{\ell u} \left(\frac{1}{2}(\bar{u}\sigma^{\mu\nu}c)(\bar{\ell}\sigma_{\mu\nu}(1+\gamma_5)\ell) - (\bar{u}c)_{S+P}(\bar{\ell}\ell)_{S+P} \right) \right]$$

Flavor changing due to diagonalization of mass matrices:

$$C^L \equiv A_L^{(\ell)} \kappa (A_R^{(u)\dagger})_2, \qquad q_{L,R}^{\rm mass} = A_{L,R}^{(q)} q_{L,R}^{\rm weak}$$

$$C^R \equiv A_R^{(\ell)} \kappa' (A_L^{(u)\dagger})_2$$

- Experimental bound $\mathcal{B}(D^+ \to \pi^+ \mu^+ \mu^-) < 3.9 \times 10^{-6}$, but this includes the 1^- resonant contributions of ρ, ω, ϕ
- Phenomenological modelling using Breit-Wigner ansatz

$$\mathcal{A}_V^{\rm LD} = \frac{a_V}{q^2 - m_V^2 + i m_V \Gamma_V} \bar{u}(k_-) \not{p}\, v(k_+).$$

- Parameters a_V fitted to $\mathcal{B}$ of resonant mode $D^+ \to \pi^+ V \to \pi^+ \mu^+ \mu^-$
- Result: resonant branching fraction

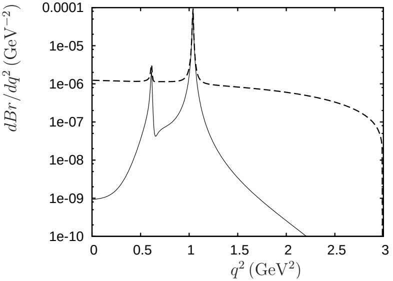
$$\mathcal{B}(D^+ \to \pi^+ \mu^+ \mu^-)_{\rm res} = (1.8 \pm 0.2) \times 10^{-6}$$

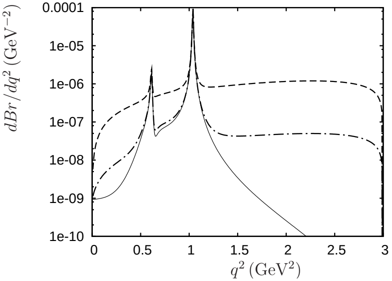
We saturate the remaining 2.3×10^{-6} of $\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-)$ exp. limit with *LQ*

$$\overline{|\mathcal{A}^{\rm LQ}|^2} = \frac{1}{16 M_{LQ}^4} \Bigg[\left(\left| C^L_{\mu c} C^L_{\mu u} \right|^2 + \left| C^R_{\mu c} C^R_{\mu u} \right|^2 \right) F_1^2(q^2)(q^2 - m_D^2)^2$$

$$+ \left(|C^L_{\mu c} C^R_{\mu u}|^2 + \left| C^R_{\mu c} C^L_{\mu u} \right|^2 \right) \left(s(q^2)(m_D^2 - m_\pi^2 - q^2 - 2(p - k_-)^2) + \frac{m_D^2}{m_c} F_0(q^2) \right)^2 q^2 \Bigg]$$

$$+ \mathcal{O}(m_\mu)$$





From $D^+ \to \pi^+\mu^+\mu^-$ we find constraints on the two combinations

$$\frac{|C^{L(R)}_{\mu c} C^{L(R)}_{\mu u}|}{(M_{\tilde{d}}/\mathrm{TeV})^2} < 0.19, \qquad \frac{|C^{L(R)}_{\mu c} C^{R(L)}_{\mu u}|}{(M_{\tilde{d}}/\mathrm{TeV})^2} < 0.16,$$

one of which is also present in $D^0 \to \mu^+\mu^-$ (helicity-lifted):

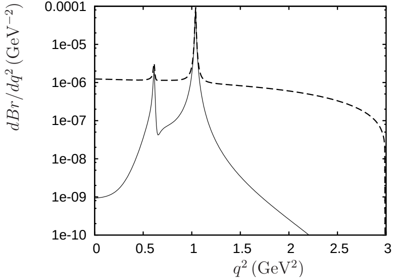
$$\mathcal{B}(D^0 \to \mu^+\mu^-) = \tau_{D_0} \frac{f_D^2 m_{D_0}^5}{256\pi m_c^2} \frac{|C^L_{\mu c} C^R_{\mu u}|^2 + |C^R_{\mu c} C^L_{\mu u}|^2}{M_{\tilde{d}}^4}$$

and from $\mathcal{B}(D^0 \to \mu^+\mu^-) < 5.3 \times 10^{-7}$ follows

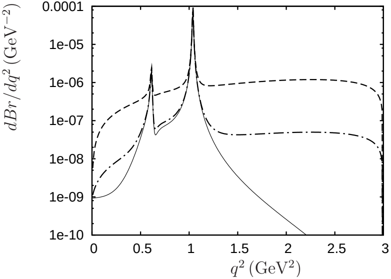
$$\frac{|C^{L(R)}_{\mu c} C^{R(L)}_{\mu u}|}{(M_{\tilde{d}}/\mathrm{TeV})^2} < 0.032$$

This bound, applied to $\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-)$ results in $9.4 \times 10^{-8} \to$
$C^{L(R)}_{\mu c} C^{R(L)}_{\mu u}$ cannot be observed in $D^+ \to \pi^+\mu^+\mu^-$

$C_{\mu c}^{L(R)} C_{\mu u}^{L(R)}$



$C_{\mu c}^{L(R)} C_{\mu u}^{R(L)}$



$\Uparrow$

ruled out

should focus on the low q^2 region

proportional to the $F_1(q^2)$ FF

Conclusions on FCNC

- inclusion of $Q = -1/3$ weak-isosinglet scalar leptoquark leads to tree-level $c \to u\mu\mu$
- $D^+ \to \pi^+\mu^+\mu^-$ sensitive to both $C_{\mu c}^{L(R)} C_{\mu u}^{L(R)}$, $C_{\mu c}^{L(R)} C_{\mu u}^{R(L)}$
- $D^0 \to \mu^+\mu^-$ only to helicity-unsuppressed $C_{\mu c}^{L(R)} C_{\mu u}^{R(L)}$
- Bound from $\mathcal{B}(D^0 \to \mu^+\mu^-)$ renders $D^+ \to \pi^+\mu^+\mu^-$ only sensitive to $C_{\mu c}^{L(R)} C_{\mu u}^{L(R)}$
- most sensitive in the low-q^2 region